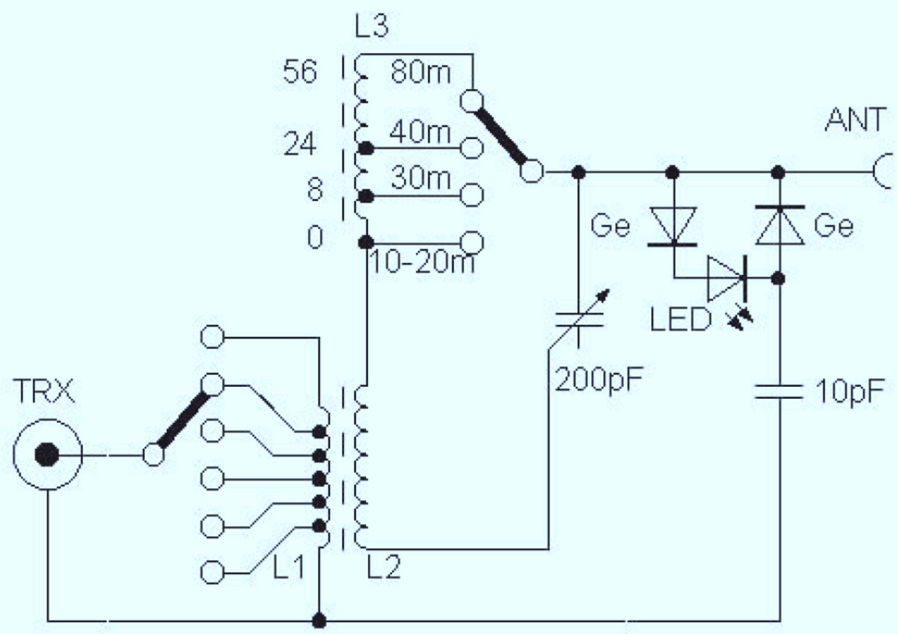
The Fuchs Antenna was introduced by Arwed Fuchs, an Austrian Radio Amateur in 1928. It was used as a high efficiency single band half-wave endfed antenna by many radio amateurs over a long period, but it was more or less forgotten when most radio amateurs started using coax-fed dipoles. In the 80s, some Swiss OMs rediscovered the Fuchs Antenna Tuner, especially for portable use. In 2000, Frank, DL7AQT, did lots of experiments with the Fuchs, and was happy to end up with a multiband version for portable use. QRPproject is now proud to make the Fuchs Antenna Tuner available as a kit. It is based on Franks' design with some small modifications we made because the variable used by Frank is no longer available.



L1: 6 x 1 turn
L2: 7 turns
on T80-2

L3: 56 turns
taped at 8 and 24 turns
on T80-2

The QRPproject Multiband Fuchs

is basically a half wave antenna. It can be used with good results at the original frequency and also at all harmonics. It is fed by a parallel circuit with inductive coupling. Tables 1 and 2 show the optimal length of a wire from 1 half-wave at 80m to 8 half-waves at 10m. As you can see, the length increases from 80 to 10m. This is because the velocity factor of 0.96 is only exact at the ends of a wire antenna. If a wire antenna is longer then 1 half-wave, the middle part must be calculated using a velocity factor of 1. In practical use, we found that the Fuchs circuit easily compensates for this difference. When the total length is a multiple of a halfwave +/- 5 %, we found no difference. As you can see, a wire length of about 21 meters makes a good antenna for 40m and higher.

Tabelle 1

Frequenz (MHz)	Halbwellen	Drahtlänge (m)
3,55	1	40,14
7,025	2	41,64
10,125	3	43,70
14,05	4	42,17
18,08	5	41,07
21,05	6	42,40
24,9	7	41,87
28,05	8	42,51

QRG	Lambda/2	Drahtlänge
7	1	20,28
14	2	20,82
21	3	21,02
28	4	21,12

During his experiments, Frank used two different designs. For the upper bands only, it was ok to use one Amidon T80-2, but this design did not work if he tried to use it from 80 to 10 meters. Some tests in the QRPproject lab using our HP Network analyzer showed that there are some extra points of resonance in the 18 MHz range. We assume that they are caused by the unused section of the core in interaction with stray capacitance. Winding the complete Fuchs circuit on TWO toroids solved the problem. There are still unwanted resonance frequencies, but they now are in the 60 MHz range, and without any influence when we tune a SW antenna.

Due to a lot of questions:

NO, there is now ground connection missing at L2!! This is part of the genious Fuchs design :-)

LED RF Indicator

The simple LED RF indicator detects the voltage at the feedpoint of the

antenna. While tuning the Fuchs circuit, when the RF voltage at this point has its highest value, the antenna is exactly in resonance, and antenna coupling of the transmitter is at its optimum.

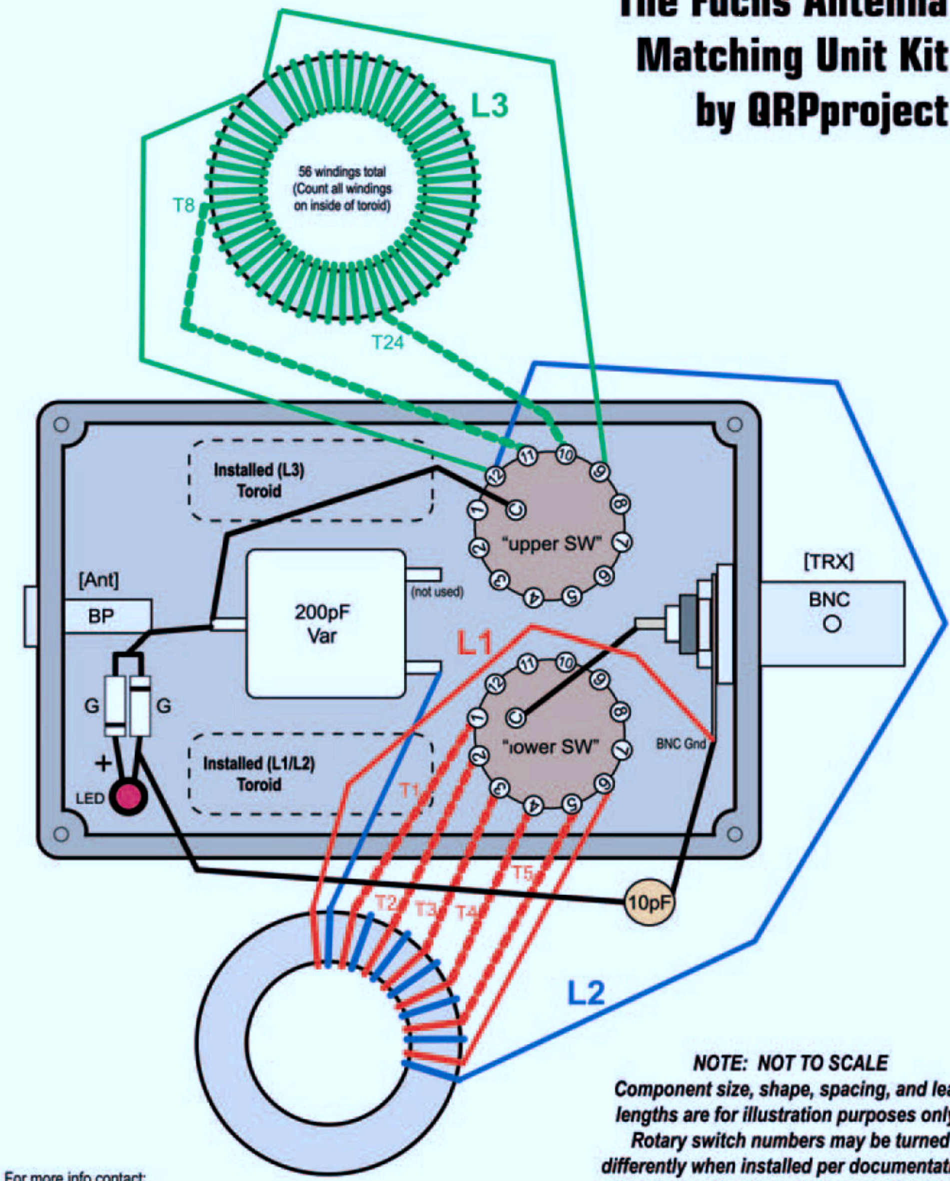
Practical experience

The Fuchs circuit was built into a 70mm x 50mm x 25 mm plastic enclosure. We used a BNC jack for the transceiver input and a banana jack for the antenna connection. It is very easy to tune. The first step is to tune the variable capacitor to loudest noise or signal in receive mode. You must switch the main coil taps to get the best result. The point of resonance is very small, so you will hear the difference between resonance and non-resonance very clearly. Usually you will find resonance at two different taps of the main coil. If so, use the one with the better L/C ratio (more L = higher Q). Now hit the transmit key in CW or a tune knob to get a transmit signal. Switch the coupling section of the Fuchs circuit to get the brightest signal at the LED RF Detector (or lowest SWR if your transmitter has a built in SWR Meter).

Parts list of the QRPproject 80-10-FUCHS kit

1 enclosure
1 variable cap
2 Amidon Toroid T80-2
2 Miniature switch 1x12
1 Banana jack
1 BNC jack
2 Germanium Diode
1 LED
3 Knobs
Enameled wire 0,5mm
Ceramic capacitor 10pF
1 manual

The Fuchs Antenna Matching Unit Kit by QRPproject



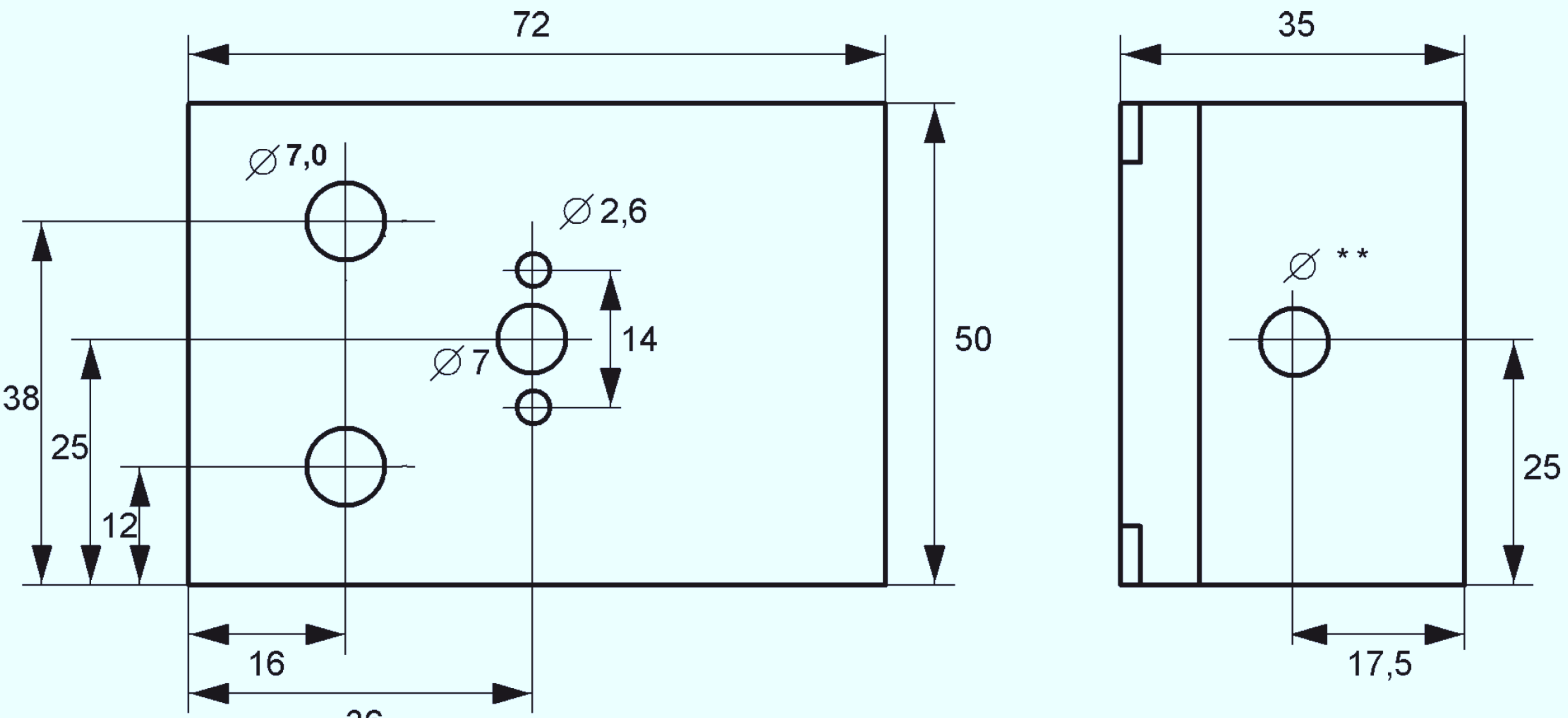
NOTE: NOT TO SCALE
Component size, shape, spacing, and lead lengths are for illustration purposes only. Rotary switch numbers may be turned differently when installed per documentation. Go by actual lead numbers on switch when soldering. See case dimensions for proper hole drilling and knob placement.

For more info contact:
support@QRPproject.de
Drawn by:
Wm Atkinson, W3IYJ

Attention: starting July 2008 we use another type of switch. It´s smaller and the common conector is placed exactly in the middle of the switch.

†1. Preparing the enclosure

Drill all holes as shown in the drawing. All distances refer to the outer side of the enclosure. The diameter of the holes are taken from the diameter of the provided parts. The BNC jack and the Banana jack



* * für Telefonbuchse 6,3 mm

* * für BNC-Buchse 8,5 mm

3. solder all remaining solder-points:
Solder a wire between the middle pin of the lower rotary switch to the inner pin of the BNC jack. Solder another wire between the middle pin of the upper rotary switch to the rotor of the variable capacitor, and another short wire from the rotor to the banana jack. The only remaining thing now is the LED RF-Indicator.

Drill a hole for the LED somewhere in the top of the box, near the banana jack. Solder the cathode of one germanium diode and the cathode of the other Ge diode to the banana jack. The other side of both diodes must be soldered to the LED: (Ge-cathode to LED anode, and Ge-anode to LED cathode.) The cathode of the LED must be connected to BNC ground using a piece of wire and the 10pF ceramic cap.

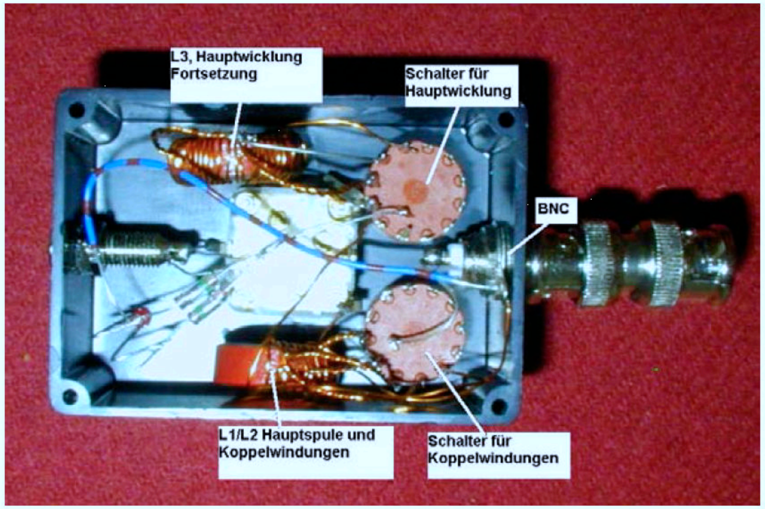
That’s all! The Fuchs circuit is now ready to use.

Remark:
By practical use we found that the Diodes plus the LED may cause intermodulation to your RX especially at winter evenings at 40m when using long antennas. If you run into this problem, remove the 10pF cap connected between the LED and ground. The LED will still work as an indicator, picking up energy by stray capacitance. It will not glow as strong as before but still enough to work as an indicator. Give it a try.

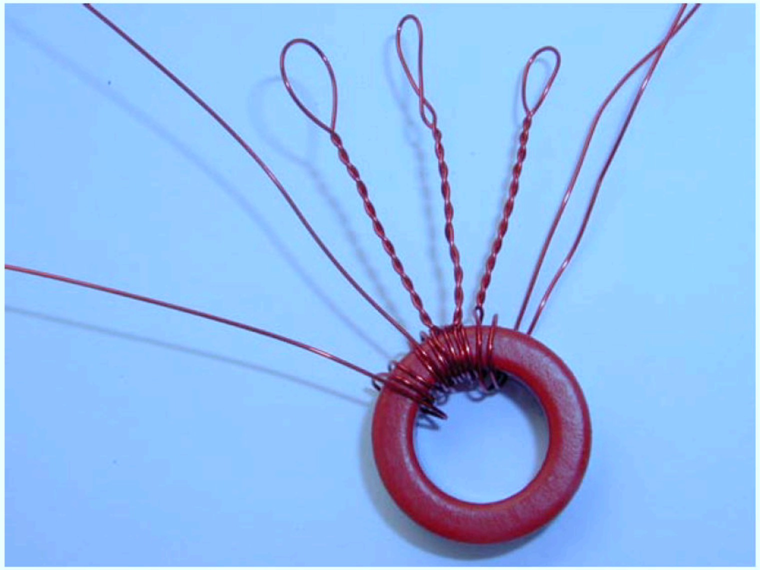
Start operating:

Connect the Fuchs using the BNC:BNC connector to your transceiver. Use a 41meter (or 21 meter) long antenna wire, connect it to the banana jack,and switch the receiver on.
At first, choose the coupling factor by switching the lower rotary switch. For 10 and 12 meters, this will probably be 1 turn; for 15, 17 and 20M, 2-3 turns; for 30 and 40M, 3-4 turns; and for 80M, 4-6 turns. Now adjust the main windings using the upper rotary switch and the variable cap. Start with the switch at its lowest position and rotate the variable cap. If you have chosen the right tap of the main winding, you will find a dramatic increase of noise if the capacitor has the right value to resonate. If there is no point of resonance, try the next tap. If the circuit is in resonance, key the transmitter and adjust the coupling for best SWR (brightest LED).
This procedure seems to be complicated, but you will find, that it is very reproducible. So, in the future, you only have to remember which tap to use for which band, and tuning will be very fast. I hope you will enjoy your Fuchs antenna tuner! It’s an excellent choice for portable use, because you will need only one port, and because it is a high efficiency tuner with very low loss.

Peter, DL2FI
If you have any questions or suggestions, please send me an e-mail, or phone: Support@QRPproject.de / +49 30 859 61 323



must be placed exactly in the middle of the front and back (short) sides, as shown on the pictures.



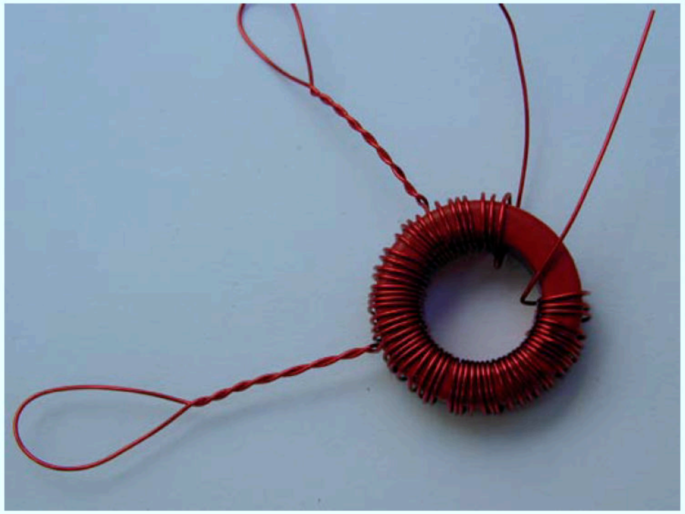
2. Winding the Toroids

L2/L1

Attentention, the pictures do not show the exact number of turns.

Remember that turns on a toroid are always counted at the inner side of the ring. Start with 7 Turns for L2. Don't spread the 7 turns over the ring, but keep the turns close together at the inner side of the ring. Leave about 6cm at both ends of L1. Now, wind L1 (the coupling winding) between L2. For these to be in phase, lay the wire for L1 parallel to the L2 wire and start at the same point, where L2 starts. Do one turn through the Ring, and then form a loop (abt 3cm diameter) and twist the loop as shown in the photo. (ATTENTION, photo does not show all windings) Do the next five turns, forming such a loop after every turn.

To see how long the twisted loops must be, put the toroid at its place just below the lower 1x2 switch (BNC right sided, banana left sided, as shown in the photo). Bend all wires to their places, and cut them to the desired length. The beginning of L2 goes to the stator of the variable cap, end of L2 to the Pin 12 of the upper rotary switch. The starting point of L1 goes to BNC Ground, first tap to Pin 1 of the lower rotary switch, second tap to pin 2, third tap to pin 3, and so on; all taps and the end of L1 to the lower rotary switch. Next step is to tin all the wire ends. We prefere the „BLOB“ method. What is the BLOB method? Using a hot soldering iron, melt a drop of solder at the end of the tip and hold it to the wire you would like to tin. Wait until the coating of the wire starts melting. You will see and smell some smoke. Don't breathe the smoke; it's not very healthy! When the coating starts melting, move the solder „BLOB“ back and forth. The result will be a nice tin coating at the end of the wire. Check to see if the tin is all around the wire. If not, do the same procedure again. When all the ends and taps are tinned, solder L1/L2 to the 1st place, as described.



Next prepare L3

Take the other T80-2 toroid. Wind 8 turns and form a 4-5cm loop as you did for L1. Wind the next 16 turns in the same direction, giving you a total of 24 and form a second loop. Now, wind another 32 turns(total of 56) Now, place the toroid above the upper rotary switch, and prepare the wires. The beginning of L3 leads to Pin 12 (junction to L1), the first tap (turn 8) leads to Pin 11, second tap (Turn 32) to PIN 10, and the end of L3 to pin 9. Again, coat the wire ends with Tin, and solder them to their places.

The FUCHS Antenna got its name from the Austrian Radio Amateur FUCHS, who first described it in 1928. It was a monoband endfed half wave dipole.

The length of the antenna wire should be a Lambda/2 or a multiple of it. For 3,5 MHz you need about 41 meters.

With the FUCHS Network it is possible to use a 41 meter wire on all bands between 10m and 80m.

Tabelle 1

Frequenz (MHz)	Halbwellen	Drahtlänge (m)
3,55	1	40,14
7,025	2	41,64
10,125	3	43,70
14,05	4	42,17
18,08	5	41,07
21,05	6	42,40
24,9	7	41,87
28,05	8	42,51

Table 1 shows the length of wire we need for a given number of half wavelengths per band.

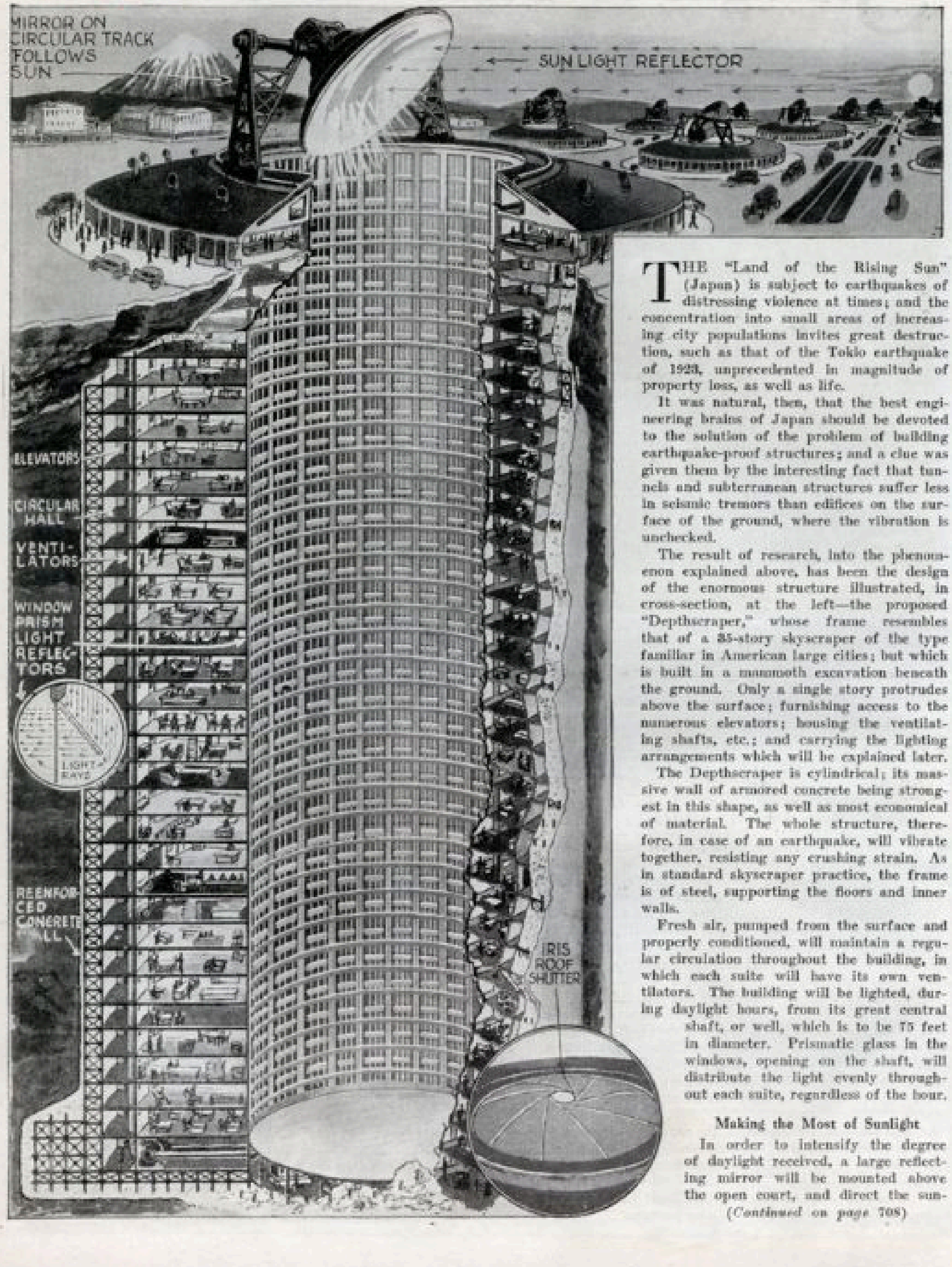
For 10m through 40m use a 21m wire.
For 10m through 80m use a 41m wire.

The QRPproject FUCHS Antenna

The network fits into a 70mm x 50mm x 25mm plastic enclosure. A BNC plug plus a BNC to BNC connector gives use the flexibility to use it with any rig which has a BNC antenna jack. Tuning is very easy. The first step is, to find the point of maximum noise / loudest signal in receive. Now with a small transmitter signal, the link is switched to lowest SWR. Ready. The FUCHS is equipped with an output indicator. Only at the point of resonance does the LED glow.

Parts list of the QRPproject Fuchs 80-10 kit
1 Enclosure
1 Variable capacitor (Poly Varicon) 340 pF
2 Amidon Torroid T80-2
2 Miniature 1x12 switch
1 Banana jack
1 BNC jack
2 GermaniumDiode (1N34)
1 LED
3 Knobs
3m enameled wire (24 AWG)
1 BNC<> BNC connector

"Depthscrapers" Defy Earthquakes



THE "Land of the Rising Sun" (Japan) is subject to earthquakes of distressing violence at times; and the concentration into small areas of increasing city populations invites great destruction, such as that of the Tokio earthquake of 1923, unprecedented in magnitude of property loss, as well as life.

It was natural, then, that the best engineering brains of Japan should be devoted to the solution of the problem of building earthquake-proof structures; and a clue was given them by the interesting fact that tunnels and subterranean structures suffer less in seismic tremors than edifices on the surface of the ground, where the vibration is unchecked.

The result of research, into the phenomenon explained above, has been the design of the enormous structure illustrated, in cross-section, at the left—the proposed "Depthscraper," whose frame resembles that of a 35-story skyscraper of the type familiar in American large cities; but which is built in a mammoth excavation beneath the ground. Only a single story protrudes above the surface; furnishing access to the numerous elevators; housing the ventilating shafts, etc.; and carrying the lighting arrangements which will be explained later.

The Depthscraper is cylindrical; its massive wall of armored concrete being strongest in this shape, as well as most economical of material. The whole structure, therefore, in case of an earthquake, will vibrate together, resisting any crushing strain. As in standard skyscraper practice, the frame is of steel, supporting the floors and inner walls.

Fresh air, pumped from the surface and properly conditioned, will maintain a regular circulation throughout the building, in which each suite will have its own ventilators. The building will be lighted, during daylight hours, from its great central shaft, or well, which is to be 75 feet in diameter. Prismatic glass in the windows, opening on the shaft, will distribute the light evenly throughout each suite, regardless of the hour.

Making the Most of Sunlight

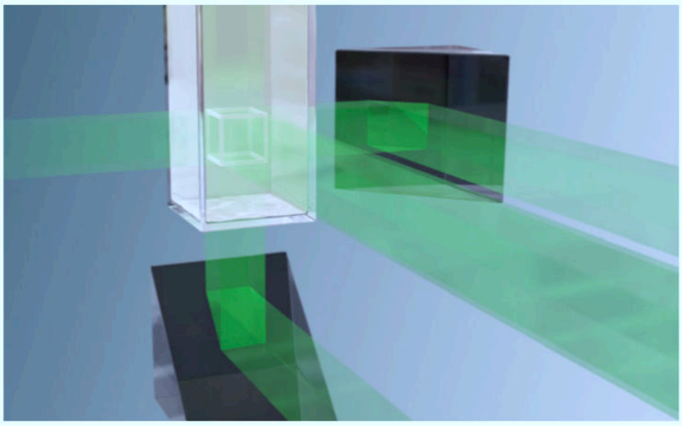
In order to intensify the degree of daylight received, a large reflecting mirror will be mounted above the open court, and direct the sun-

(Continued on page 708)


SHANGHAI EARTHSCRAPER "DEPTHSCRAPER"

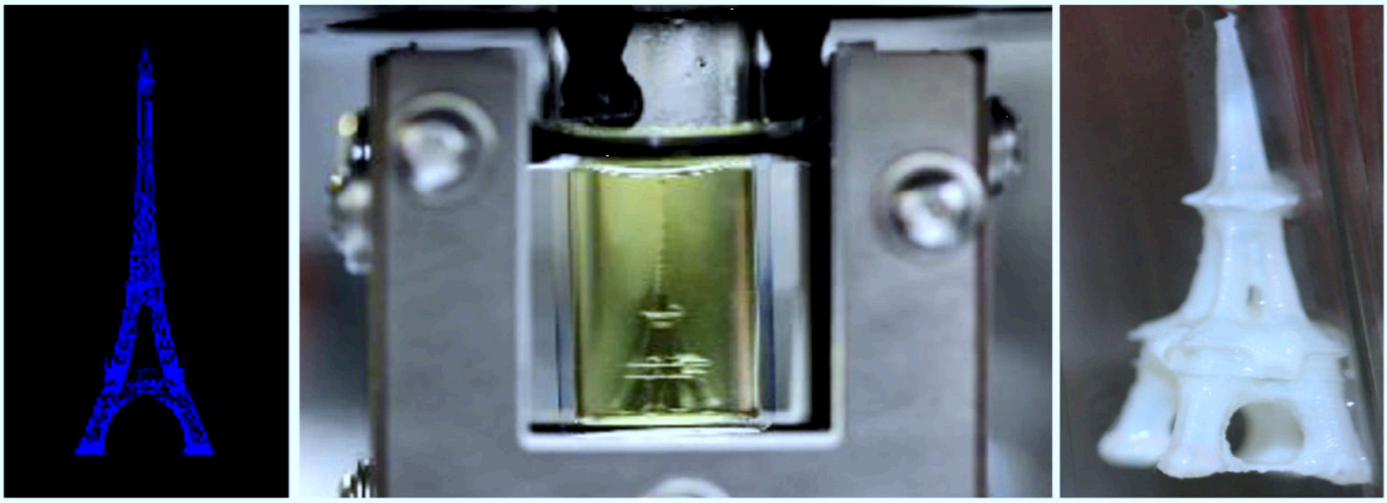
SET hundreds of years in the future, *Star Trek* depicts crew members wielding flip-to-open communicators to make surface-to-ship calls and using a replicator to instantly materialize food or spare parts. In the real-life present, smartphones have already outpaced those fictional communicators in many ways, and now we are on the verge of achieving another final-frontier technology, one capable of creating three-dimensional (3D) objects all at once rather than one piece at a time.

Researchers at Lawrence Livermore, in collaboration with the Massachusetts Institute of Technology, the University of California (UC) at Berkeley, and the University of Rochester, have invented two methods of volumetric lithography—using light beams to fabricate complex 3D polymer structures in one go instead of building them gradually. Livermore microtechnology engineer Maxim Shusteff says, "We wanted to explore how to make a 3D part all at once, and we decided that the easiest way would be to use light and some transparent medium. Immediately 3D holograms came to mind. Could we generate a hologram in a photosensitive material, so that the hologram cures into a physical object?" With the Laboratory's holographic and computed axial lithography technologies—both developed with support from the Laboratory Directed Research and Development (LDRD) Program—the answer appears to be yes.

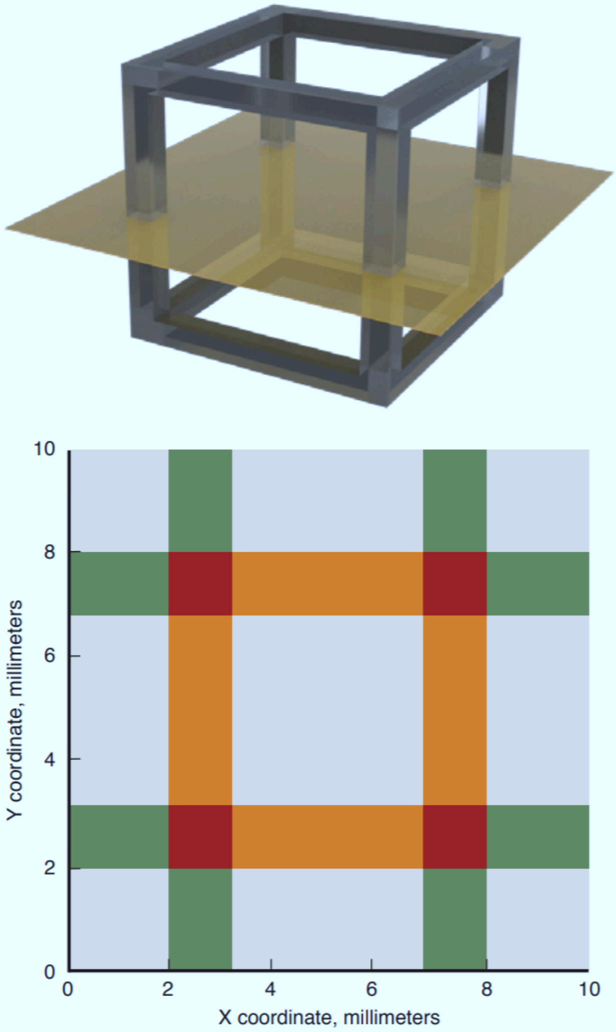


A simulation depicts holographic lithography, which begins by creating a three-dimensional (3D) hologram of the object to fabricate. A laser beam is patterned by a spatial light modulator and split into three image projection beams (green), each representing a different view of the object. Prism mirrors direct beams into a chamber containing light-sensitive resin. The resin cures wherever the three beams intersect, forming the object.

These new processes are set to energize the realm of additive manufacturing—also known as 3D printing—by combining it with lithography, which is already widely used to make microchips using photosensitive materials. In traditional 3D printing, parts are constructed layer by layer using a point source, such as a nozzle or a focused laser beam that moves back and forth across a surface to deposit or melt material in a desired pattern. In such printing approaches, an entire two-dimensional (2D) layer may be patterned all at once. However, these techniques all have drawbacks. Shusteff explains, "The layer-by-layer approach is slow. For example, if your part has a hundred layers and each layer takes a minute to print, then the part takes almost two hours to complete. In addition, the resulting parts can have zigzagging edges. This roughness is almost always undesirable. Furthermore, unsupported structures or



Using computed axial lithography, a 3D model of the Eiffel Tower is formed. (left) Each video frame shows the shape from a slightly different perspective. (middle) Inside a rotating chamber, the beam reacts with light-sensitive resin, which begins to harden. (right) After about 2 minutes of exposure, the resin solidifies into the 3D part.



(top) A cubic lattice is shown as an example of a 3D object that can be formed by holographic lithography. The plane marks the cross section shown in the bottom image. (bottom) The relative intensity of light in the projection beams for the cross section is shown. Intensity increases with the number of beams intersecting—three beams (dark red), two beams (orange), one beam (green), and no beams (beige).

disconnected islands of material that will later connect to another layer by an overhang or a span cannot be formed layer by layer. Our new approach of creating objects in 3D all at once overcomes these limitations."

Holographic Lithography

In holographic lithography, the first step is to generate a hologram of the object. Next, the hologram is broken down into three projections each representing a different orthogonal view, usually front-to-back, right-to-left, and top-to-bottom. A diode laser generates a 532-nanometer primary beam with a power of 5 to 50 milliwatts, and the beam is widened by passing through an array of optical components. After striking a spatial light modulator—an array of liquid crystal pixels on a silicon surface—the beam is patterned into the three projections spaced apart from each other inside the beam and which together comprise the single 3D image.

Refined by additional optics, the projected image overlaps two prism mirrors and a glass chamber, which contains a resin made of a photopolymer—polyethylene glycol diacrylate—with a small amount of photoinitiator. Two of the three composite image segments are directed by the mirrors into the chamber at right angles while the third projection shines head-on into the chamber. As these beams perpendicularly intersect in the chamber, the free-floating 3D structure forms in the resin as its photopolymer absorbs the light energy. A single exposure lasts only 1 to 20 seconds. Objects up to a few millimeters in size have already been successfully fabricated.

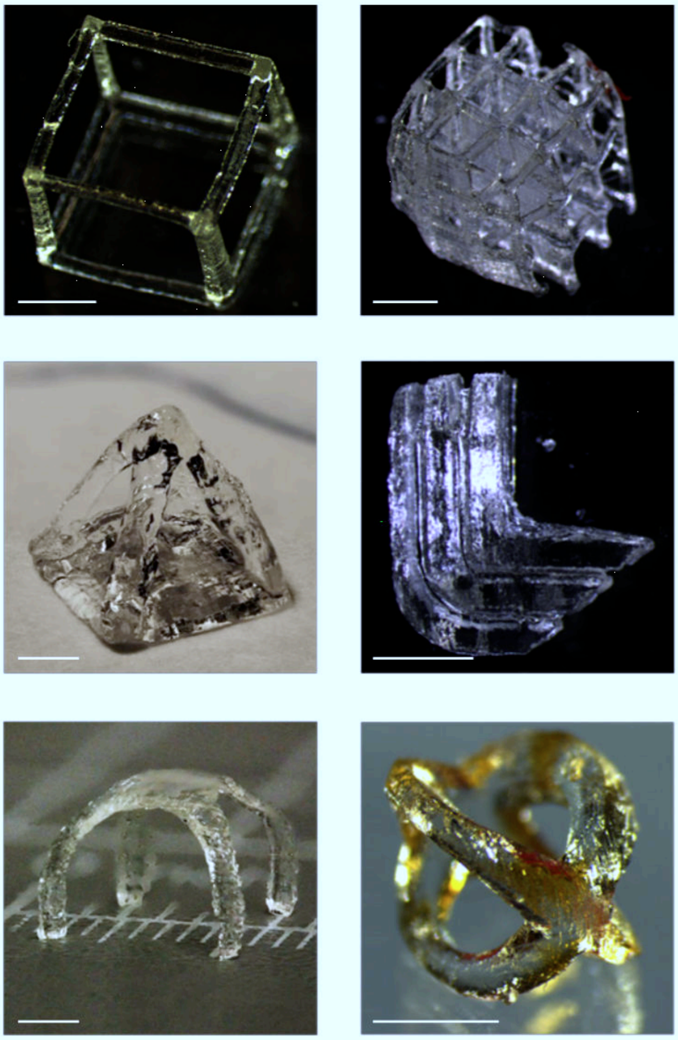
Superposition and Materialization

The absorption of light energy by the photoinitiator causes free-radical polymerization, a chemical reaction in which photopolymer molecules grow and link together. As the molecules interconnect by crosslinking, the material first achieves a gelatinous state and then finally cures into a 3D solid. In the case of a cubic lattice, for example, each projection beam has a cross-sectional shape like a square with thick sides and passes through the entire volume of resin like a square cylinder. Overlapping of the separate projections is called superposition, and at these spots the light is two to three times stronger than that of a single projection beam. The greater the intensity of light, the faster the curing occurs. Where all three projection beams converge to produce the maximum amount of light energy is where the object forms as the light energy exceeds the photopolymer's dose threshold and crosslinking occurs. If three-beam superposition does not occur, the resin does not fully cure because the threshold is not exceeded.

Shusteff adds, "Part of the LDRD study was to determine where exposure should occur, how long exposure should last, how much light to use, what concentration of photosensitive material can achieve the desired curing rate, and how to assess the degree of curing. In short, a timing game is played. For example, if exposure is too long, the structure overcures, and resin outside of the three-beam intersections also starts to solidify."

Computed Axial Lithography

Forming hologram projections with a spatial light modulator is a complex, demanding process. The laser must be stringently aligned by many optical components, including multiple lenses and filters.



Photos show some of the hundreds of objects successfully fabricated with holographic lithography. The cubic lattice from the previous figure is shown in the top left. Each scale bar represents 2 millimeters.

Measurements are also required to control speckle, that is, noise from the interference of coherent light. Shusteff describes another challenge: "The projection beams are basically like extrusions or collimated light and so cannot have features in the depth dimension. This characteristic imposes geometrical limitations on what structures can be made. To investigate the true limitations of geometric shapes, we developed an outgrowth project." That investigation of possible geometries entailed asking whether the three projection beams could be aimed in other directions, not only perpendicular to one another. The team turned their attention to nonholographic projections and developed a method called computed axial lithography (CAL), which is a similar to the computed tomography used in medical applications but uses visible light instead of x rays. Brett Kelly, a graduate student from UC Berkeley, spearheads this effort at Livermore.

In CAL, the system generates a video portraying the complete rotation of projections of the 3D object to be fabricated. Kelly explains, "Instead of using three images, we use a sequence of 1,440 images, or 4 per degree of rotation." For roughly 1 to 3 minutes, the video images travel through a lens and into a resin chamber whose rotation rate is synchronized with the video frame rate. Each image is a different 2D pattern of light and enters the resin from a different angle. Inside the resin, the light intensity increases through superposition. Kelly adds, "By summing up all these carefully designed images, we create a distributed 3D energy dose inside the resin. With multiple rotations, the dose becomes sufficient to cure desired regions while leaving undesired regions in liquid form." The resin used is more viscous than that in holographic lithography, but the same crosslinking process forms structures on the centimeter scale. The structures cure upon completing up to three full rotations. Because CAL uses time-multiplexed images and a weaker light source—requiring more time for the dose to exceed the photopolymer's light energy threshold—build rates are currently slower than those of holographic lithography. However, holographic lithography's geometric constraints of are overcome.

Shusteff sees holographic lithography and CAL as complementary. "We may not always be able to fabricate a part by spinning it around in CAL or not always have access to all sides to use holographic lithography. However, the chances are we can make any structure using one technique or the other or some combination of both." The researchers are now eagerly looking to further push the boundaries of these technologies. What other materials can be used? Can the size of a shape be scaled up and down? How can the resolution be improved? What other limitations are out there? Determined work will answer these questions. Says Shusteff, "These are certainly the directions in which we hope to take this promising technology in the future."

—Dan Linehan

Key Words: additive manufacturing, computed axial lithography (CAL), holographic lithography, Laboratory Directed Research and Development (LDRD) Program, laser, photopolymer, spatial light modulator (SLM), superposition, three-dimensional (3D) printing, tomography.

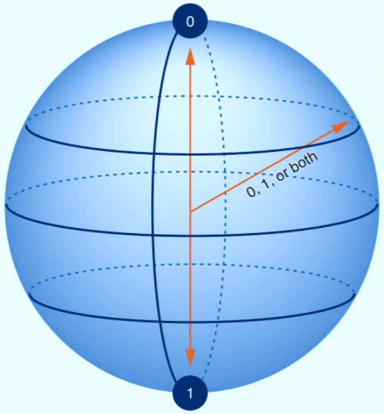
For further information contact Maxim Shusteff (925)423-0733 (shusteff1@llnl.gov,).

Ongoing activities include demonstrating a fully programmable quantum computing system, improving superconducting materials and devices, deploying quantum sensors, and developing quantum algorithms. Progress has been encouraging, with Livermore recently deploying two functional quantum computing test beds.

The Quantum Lexicon

At first glance, parallel computing systems such as Livermore's existing supercomputers may seem equivalent to quantum computers in that all perform multiple operations simultaneously. However, the key difference is in how the two fundamentally tackle computing problems. A classical computer uses on/off transistors to store and process information, encoding data in binary digits, or bits, in one of two states—0 or 1. In contrast, a quantum computer operates on the principles of quantum physics, storing data in quantum bits, or qubits (pronounced "cue-bits"). Livermore's qubits are superconducting electrical circuits that can exist in multiple simultaneous states—0, 1, or both. This principle of superposition is analogous to mathematically representing the state of a heads-or-tails coin flip whose outcome is still literally up in the air. The concept was first illustrated by Erwin Schrödinger's famous 1935 thought experiment wherein a hypothetical unobserved cat is both alive and dead—but found to be one or the other when observed.

Using qubits for computation increases processing power exponentially. Two qubits can store data in four states concurrently—00, 01, 10, and 11. A 64-qubit quantum processing unit (QPU) is equivalent to 2^{64} bits—16 exabits—in a classical computer. For any number (n) of qubits, a quantum computer could perform 2^n operations at the same time. A classical computer would take far longer to do so—in some cases, years compared to seconds. This promising leap in computing power is possible only if the superposition state can be precisely controlled to remain coherent. Otherwise, the qubit system can generate errors as it processes information simultaneously. Coherence requires preservation of the relationship between different quantum states so that superposition results, which in turn requires that changes to qubits can be reversed.



Superposition is a major principle in quantum physics, occurring when particles exist in multiple states. This phenomenon allows a single quantum bit, or qubit, to represent 0, 1, or both. In contrast, a bit in classical computing can only represent 0 or 1.

Prolonging coherence is the key to sustaining quantum calculations. The smallest changes in the environment surrounding a qubit can cause a loss of coherence, also called decoherence, so scientists are keen to reduce interference from electromagnetic waves, temperature variations, and other variables in and around quantum hardware. Quantum computing—and quantum-coherent devices in general—therefore requires both using precisely controlled low-energy pulses to sustain superposition states and preventing other energy sources from disturbing those states. "We are working at the opposite end of the energy spectrum from explosives or galactic events," explains Laboratory physicist Yaniv Rosen. "We are studying energies 100 million billion times fainter than the energy expended in a mosquito's flight, down to 20 microelectronvolts."

Decoherence and other system noise can be sources of error in quantum computing. In classical computing, error correction helps make systems fault-tolerant by ensuring reliable data delivery and reconstruction, and the viability of quantum computing also depends on achieving such goals. DuBois points out, "No one experimenting in this field has yet demonstrated successful error correction, which is analogous to break-even in nuclear fusion."

A Supercool Facility

A quantum computer does not look like a classical computer. Its refrigerator does not resemble a typical refrigeration unit, for instance. At Livermore, a quantum processor relies on superconductivity to reduce electrical resistance and interaction with the environment. The superconductive processor, consisting of particles in quantum circuits, is operated at extremely cold temperatures so that scientists can control the circuits' quantum states. This approach may offer the best chance of achieving coherence goals. The sophisticated cooling infrastructure recirculates helium-3 and -4 isotopes through layers of increasing coldness, reducing the interior temperature to –273.1°C (0.007 kelvin). The dilution refrigerator operates under vacuum and is electrically shielded to minimize heat leaks and environmental noise.

Qubits are seated inside the refrigerator and connected to a suite of electronics that control superposition with microwave pulses. An arbitrary waveform generator provides gigahertz frequencies and amplitudes to interact with the qubit, and an oscilloscope monitors the input signals.

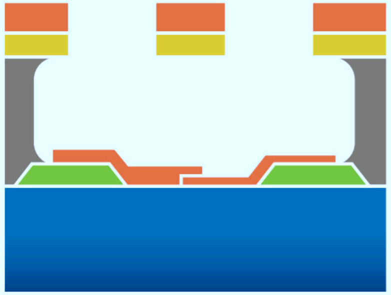
The results of these manipulations are sent to an analog-to-digital converter to verify signal fidelity, and the calculation results are read on a standard computer. Indeed, classical computing plays an important role in calibrating, running, and maintaining the Laboratory's quantum computing test beds. The Livermore team codes instructions for pulse shape and frequency in the Python programming language and uses HPC software to adjust designs for pulse control and other variables.

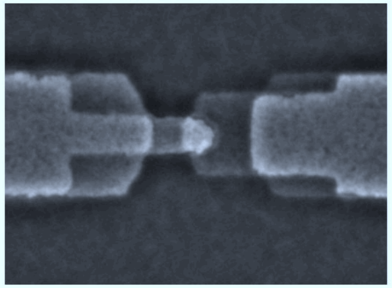
Although many of these components are available commercially, no instruction manual exists for a fully integrated quantum system. The team's hands-on experience and troubleshooting skills grow daily as they supply their own technical support. Eric Holland, Livermore's chief quantum systems architect, explains, "We are assembling quantum computing components in ways others have not. Livermore is blazing a trail." For example, the Laboratory's qubits are housed inside canisters attached to the bottom of the refrigerator. Made of gold-plated copper to prevent oxidation and maximize thermal contact in a vacuum, the cans are designed, built, and coated at the Laboratory before being sent offsite for annealing. Special shielding protects the qubits from stray magnetic fields and prevents light leaks. Each test bed holds four cans, allowing multiple experiments to run simultaneously.

This machinery is inherently fragile. Rosen says, "On paper, a quantum system design can seem perfect, but the environment really comes into play when implementing the design." However, DuBois cites the Laboratory's expertise in HPC, engineering, materials science, cryogenic physics, and quantum physics as

Inside a test bed's dilution refrigerator, gold-plated cans contain qubits, which are connected by wires to the rest of the assembly. Recirculating helium progressively cools the structure from top to bottom, with each circular plate introducing a colder phase. (Photo by Carrie Martin.)

a potentially game-changing combination in solving the quantum computing puzzle. “Livermore’s people have a well-defined vision of how to advance this field,” he says. The Laboratory’s two test beds are similarly assembled but serve different purposes—one for quick tests and prototyping and the other for mature experiments. The former was installed in late 2017, while the latter came online in early 2018 to support the ASCR Quantum-Enabled Simulation (AQuES) Testbed Pathfinder Program, which brings Lawrence Livermore and Lawrence Berkeley national laboratories together to pursue diverse research and development in quantum computing.





A Josephson junction is the key component of superconducting qubit circuitry. (top) The Laboratory’s fabrication process, shown in side view, includes precisely controlled deposition of layered materials (green, orange, yellow) on a substrate (blue). (bottom) Scanning electron microscopy shows a top view of a complete Josephson junction after deposition.

Building Better Qubits

Livermore scientists are developing quantum computing components alongside a new class of superconducting materials for low-energy regimes. These efforts span qubit design, QPU configuration, quantum chip circuitry, and quantum materials science. (See *S&TR*, March 2016, pp. 17–19.) Holland explains, “The design space is ripe for exploration. Our internal investments allow us to question others’ approaches.” Classical computing advancements typically focus on planar chip design, and industry’s prevailing quantum chip architecture is a two-dimensional (2D) lattice of qubits, each controlled by a separate oscillating signal input. However, both 2D and three-dimensional (3D) designs are being pursued at the Laboratory. DuBois states, “For better efficiency, we are trying to achieve the same computational power with one input port per system, not per qubit—a completely different paradigm for controlling the basic unit of a scalable quantum computer.”

Furthermore, industry typically offers nearest-neighbor connections between qubits, which means lattice arrays increase as more neighbors per qubit are added, making the device less efficient as it grows in size. By the end of the 5-year AQuES Testbed Pathfinder Program, the Livermore team intends to stand up a working 20-qubit QPU with all-to-all connectivity—any pair or trio of qubits, and any combination of pairs or trios, will be interconnected. “This QPU size is the equivalent of a matrix of about a million squared, which is a good starting point for an HPC system to simulate,” says Holland.

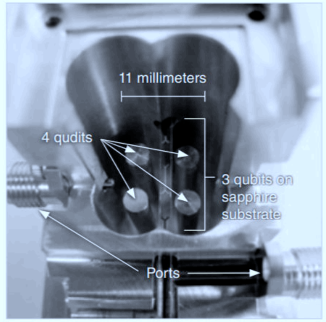
The team is experimenting with several designs for manufacturing and positioning qubits, all aimed at minimizing energy loss and error rates while maximizing performance. The Laboratory’s qubits are based on Josephson junctions, in which two superconducting materials are connected by an insulating link. In an environment cooled nearly to absolute zero, this design allows current to flow between the superconductors with very little voltage applied. “Josephson junctions are the essential ingredient in superconducting QPUs,” says Holland. Using electron-beam lithography and evaporation, Josephson junctions are created with overlapping layers of aluminum and oxidation coatings deposited onto a substrate.

An effort at design improvement combines qubits in a new configuration known as a “qudit.” This highly efficient, multidimensional arrangement of qubits stores data in more than two states and with lower error rates. The larger the qudit, the more qubits it represents and the faster its calculation potential. A new, homegrown QPU design, nicknamed the quad core, begins with qubits fabricated on sapphire wafers, which are then cut into strips. Inside the high-purity aluminum core, a three-qubit strip is flanked by four qudits. This layout results in all-to-all connectivity.

Do-It-Yourself Materials

Beyond serving as the building blocks of quantum computing, qubits also help Livermore researchers probe low-energy and -temperature systems in general, which in turn helps the team build better qubits. Rosen explains, “Not many institutions are investigating materials development for quantum systems. While others try to improve construction, we also strive to understand the root of the problem, such as which material properties are affected by miniscule energy changes.” For instance, Rosen studies surface defects, which behave completely differently from bulk defects. Disruption in surface-level energy is a potential source of decoherence in quantum circuits and qubits.

Livermore researchers are developing 2D quantum chips containing unique resonator geometries. A 2D resonator is a pattern of conductive material used to optimize oscillation signals, visually resembling a television antenna flattened onto a plane inside a microchip. The widths of each tine and the spaces between them affect electrical flow through the resonator. In recent experiments, Rosen used the Laboratory’s quantum computing test beds to measure surface defects in superconducting aluminum resonators. The test bed’s ultracold environment reduces electronic interference so that the team can track a single photon’s passage through a resonator pattern. The longer the photon stays inside the resonator before “ringing down,” the longer the coherence time. Rosen summarizes, “If we can store a photon indefinitely by controlling or mitigating surface defects, we can extend the quantum computing time limit.”

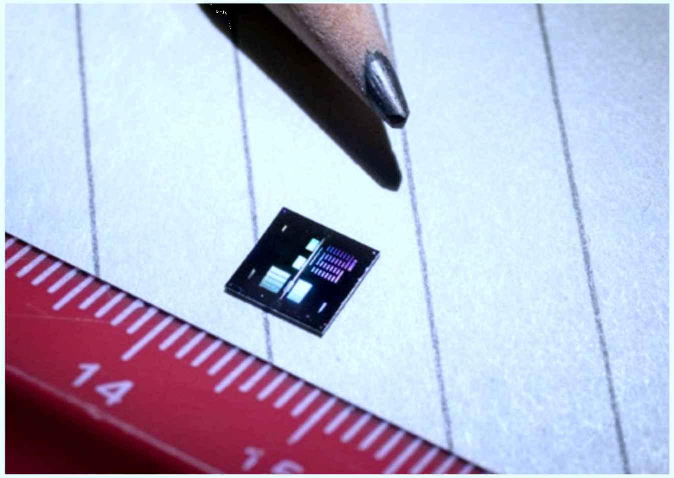


Livermore’s innovative “quad core” QPU provides all-to-all connectivity among three qubits and four qudits. The design also improves resource efficiency with multipurpose ports that can be used for inputs or outputs.

Another project uses Livermore’s additive manufacturing capabilities to create a 3D resonator whose conical cavity may prolong quantum states. “Sources of energy loss in 3D resonators are different than in 2D resonators,” explains Rosen. The team seeks to understand energy loss in resonator cavity areas of high current and high electric field. They are also investigating materials with high kinetic inductance, a property describing the energy stored in a superconductor’s bound electrons. Experiments run on Livermore’s test beds characterize electrical resistance along the cavity’s surface.

The superconducting 3D resonator is made of a common alloy of titanium, aluminum, and vanadium known as Ti64, often used in additive manufacturing at Livermore. The cylindrical device measures 25 millimeters in diameter and is fabricated with selective laser melting because conventional machining cannot create the special cavity shape. Investigating and testing the Ti64 and other cavity systems augment Livermore’s approach to quantum technologies. In 2018, physicist Gianpaolo Carosi led a workshop at the Laboratory’s Livermore Valley Open Campus to review the latest in cavity research. Attendees hailed from other national laboratories, international organizations, and academic institutions. He says, “Better cavities mean better qubit control. We see much synergy in developing these systems for superconducting qubits and accelerator experiments.”

In addition, Laboratory researchers are collaborating with the University of California at Berkeley to explore other types of resonator materials, such as amorphous silicon. Rosen says, “Growing crystalline materials for 2D resonators is very difficult, so we are considering different



Fabricated with the Laboratory’s photolithography equipment, an aluminum quantum chip is ready for testing. This chip contains 5 resonator layouts, each up to 1 millimeter wide. (Photo by Randy Wong.)